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A. Kalis, T. Antonakopoulos and V. Makios

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A PRINTED CIRCUIT SWITCHED ARRAY ANTENNA FOR INDOOR COMMUNICATIONS

Antonis Kalis, Theodore Antonakopoulos, *Senior Member, IEEE* and Vassilios Makios, *Senior Member, IEEE*
Department of Electrical Engineering & Computers Technology, University of Patras,
26500 Rio Patras, Greece

ABSTRACT

This paper presents a new printed switched array antenna suitable for indoor mobile communications. The antenna uses printed active elements and produces either omni-directional or many directional overlapping patterns. The omni-directionality is needed in order to implement the collision avoidance algorithms in next generation wireless systems, while directional patterns are needed to effectively confront the problems induced by the noisy indoor channel to the highly demanding wireless applications. An electromagnetic simulation tool was used to evaluate the antenna design.

1. INTRODUCTION

New generation wireless applications are very demanding in terms of aggregate throughput, bit-error-rate, cost and size. The indoor wireless channel induces several problems to these goals, due to high levels of multi-path fading and co-channel interference. The use of antenna pattern diversity has shown great effectiveness in overcoming these problems and recent wireless protocols have integrated such schemes [1]. On the other hand, current indoor wireless applications use omni-directional radiation patterns in order to implement collision avoidance algorithms, thus making omni-directional antennas a standard that could not be ignored in the design of next generation systems. This paper proposes a new switched beam array of printed linear slot active elements, that may produce either an omni-directional or multi-directional overlapping patterns. Omni- or bi-directional antennas and switched beam arrays have already been reported in the literature [2], [3], [4], [5], but these designs either produce a small number of beams [2], cannot be implemented on a printed circuit board [3], or use monopole elements that are unsuitable for indoor mobile communications. The design proposed in this paper integrates aesthetics, low cost design and beam control, and may produce a large number of omni-directional or directional radiation patterns.

Section 2 presents a concise description of the available antenna technologies and clarifies the need of using switched array antennas in consumer products. Section 3 highlights the proposed slot antenna element, including results on the element's radiation pattern, current distribution and mutual coupling characteristics. Finally section 4 presents the array design with results on its radiation patterns.

2. DIRECTIONAL ANTENNA TECHNOLOGIES

Radiation pattern diversity can be achieved either by the use of adaptive arrays, phased arrays or switched arrays. Adaptive and phased arrays present optimum beam-forming characteristics, but seem unattractive for portable applications. These array implementations include a number of signal paths equal to the number of elements of the array. All signal paths should be carefully designed in order to eliminate any phase differences between different paths. Each signal path has a complex weight that is realized by phase shifters and gain controlled low-noise amplifiers. These weights are controlled by the baseband processor, in order to optimize the array radiation pattern characteristics. In the baseband part of the system a large number of power consuming fast Fourier transforms (FFT) have to be computed, in order to produce the correct weights for each signal path. The complexity of this design makes it unsuitable for low-cost, low-power mobile applications.

Switched arrays have the advantage of simplicity, since pattern diversity can be achieved by controlling the state of a number of RF switches, but produce a limited number of beam patterns. In switched arrays there is only one signal path from the baseband to the antenna. The antenna diversity is achieved either by changing the input impedance of a number of elements of the array (switched parasitic arrays), or by driving more than one of the array elements (switched active arrays). In consumer mobile indoor communications, the need for simplicity and low cost designs, in expense of beam reduction, but with minimum degradation of system performance, makes the switched array solution more feasible.

Many proposals have been made for implementing switched arrays, using monopole elements [4], [5]. These arrays use

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resonant monopole antennas that may be used either as active or parasitic elements. Such arrays have been tested and they have given satisfactory results concerning pattern diversity and ease of use. Unfortunately, monopole elements are considered unsuitable for mobile applications due to aesthetics, ergonomics and cost of production. Therefore, a printed array antenna with similar characteristics would be most suitable for indoor mobile applications.

Among the different planar antenna designs, including resonant slot, patch and tampered slot antennas, the former are reported to integrate high efficiency, moderate bandwidth and small dimensions. Moreover, resonant slot antennas retain fairly constant mutual coupling effects, when placed in close proximity to each other, regardless of the inter-element space and angle [6], [7]. Motivated by those characteristics, we designed a slot antenna structure that produces an omni-directional pattern, similar to that of a monopole placed over a large ground plane. The new slot element is presented in the next section.

The method we used in order to evaluate the proposed design was the method of moments. The antenna topology was tested using two commercially available software packages, with similar results. The discretization of the geometry is done automatically by the software package, with the use of a mixed-potential integral equation (MPIE), which in its general form is given in Equation 1.

$$\iint d\,S\,\overline{\overline{G}}(r,r')\cdot \mathrm{J}(\mathbf{r}) = \mathrm{E}(\mathbf{r}) \qquad (1)$$

where $\mathrm{J}(\mathbf{r})$ represents the unknown surface currents and $\mathrm{E}(\mathbf{r})$ the known excitation of the problem. The Green's dyadic of the layered medium acts as the internal kernel. The unknown surface currents are discretized by meshing the planar metalization patterns and applying an expansion in a finite number of subsectional basis functions $\mathrm{B}_1(\mathbf{r}), \ldots, \mathrm{B}_N(\mathbf{r})$:

$$\mathrm{J}(\mathbf{r}) \approx \sum_{j=1}^{N} \mathrm{I}_j\, \mathrm{B}_j(\mathbf{r}) \qquad (2)$$

The standard basis functions used in planar EM simulators are the subsectional rooftop functions defined over the rectangular and triangular cells in the mesh. Each rooftop is associated with one edge of the mesh and represents a current with constant density flowing through that edge. The unknown amplitudes I_j, for $j = 1, \ldots N$ of the basis function expansion determine the currents flowing through all edges of the mesh.

For evaluating the antenna geometry, the most crucial parameters are the s-parameters and the radiation pattern. These are directly related to the total current, which is the integral of the current density, instead of the current density itself. The method of moments (MOM) codes using rooftop functions in non-uniform cells, are reported to be very accurate in predicting the total current on the transverse direction even when using a small number of cells in the transverse direction.

3. PRINTED SLOT ANTENNA ELEMENT

The requirements of an indoor mobile application induce several restrictions to the development of the slot antenna. These restrictions include small size (less than $\lambda_g/2$ for the biggest dimension), high efficiency, bandwidth of 100MHz and a radiation pattern similar to that of a monopole. The later is considered vital for ad-hoc indoor communications, supported by many present wireless protocols, where on-the-horizon coverage is needed.

Printed slot antennas are already reported in the literature. However, most of these either do not produce a radiation pattern suitable for our application, or are unsuitable for use in an array antenna, due to their large size. Printed antennas that may produce the desired pattern, whether these are patch or slot antennas, have a maximum dimension close to λ, and

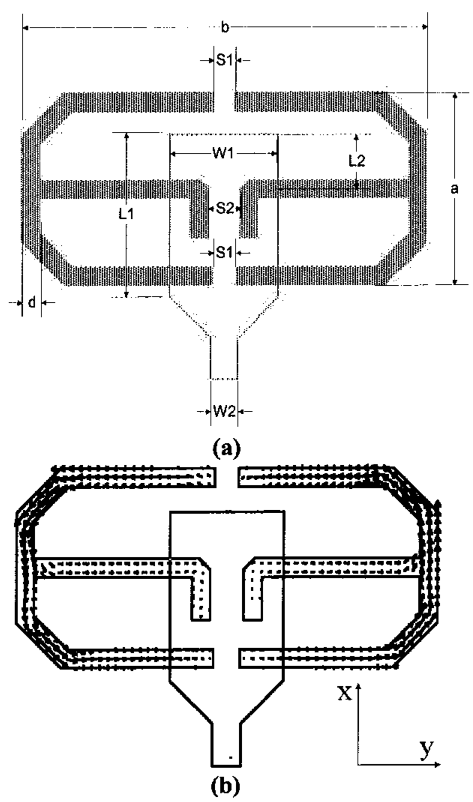

Fig 1: Slot element geometry (a) and current distribution (b) for slot dimensions: a=12.52mm, b=18.6mm, d=0.8mm, W1=5.6mm, W2=2.5mm, L1=7.7mm, L2=3mm, S1=1.1mm, S2=1.42 at 5.2GHz

they operate in the TM_{21} mode of resonance. We therefore had to develop a slot antenna that would be small in size, and also operate in the above mode. The geometry of this element that is resonant in 5.2 GHz is shown in Figure 1a.

The slot element is fed by a 50 Ohm terminated microstrip line. This feeding technique produces a current distribution on the element, similar to that of a TM_{21} mode resonance of a microstrip patch antenna, while keeping the slot length smaller than $\lambda_g/2$. The current distribution of the antenna is shown in Figure 1b. From the current distribution, the functionality of this geometry can be described. The two external arms of the antenna are of resonant length, and they are center fed from the central co-planar waveguide (CPW) like structure. The bent shape of the external arms allows a considerable amount of current to circulate in the y direction of the antenna. Moreover, the two symmetrical slots produce symmetrical currents in the y direction, which are similar to these of T_{21} mode of a microstrip patch. Such a current distribution would otherwise need a resonant length of λ in the same direction, to be produced. In this mode, peak gain is obtained near polar angles of 90^0, enabling ad-hoc network communications and is preserved nearly constant up to polar angles of 40^0. The small dimensions of the slot element enabled us to form arrays with an inter-element space equal or less than $\lambda/2$, in order to avoid the problem of grating lobes.

The design was placed on an infinite ground plane, over a substrate with a dielectric constant of ε_r=2.2 and a height of h=0.813mm. The radiation pattern of the element, shown in Figures 2a and 2b, is omni-directional over the ground level, while a small amount of power is radiated for theta above 90 degrees. This results in a directivity of 4.28dBi. The azimuth radiation pattern is not purely symmetrical. This is caused by the asymmetry in the feeding of the element. A symmetrical pattern could be produced by the use of two feeding lines, but in this case the mutual coupling between the feeding lines significantly reduces the radiation efficiency of the antenna, even though the antenna efficiency remains on the same high levels. The impedance bandwidth of the element is shown in Figure 2c. The slot element radiates with an efficiency of above 80% at 5.2 GHz, over a bandwidth of 2% for VSWR<2, thus covering the 100 MHz bandwidth specifications of HIPERLAN and IEEE802.11a.

3.1 Mutual coupling between proposed elements

In order to form an array that can produce an omni-directional pattern, the characteristics of mutual coupling between elements should be studied. For example, when two or more elements are placed close to each other, they may experience mutual coupling depending on their proximity and shape. The total current in the element is the sum of the induced currents and the driven current. Thus, the current distribution in an element of an array is generally different to

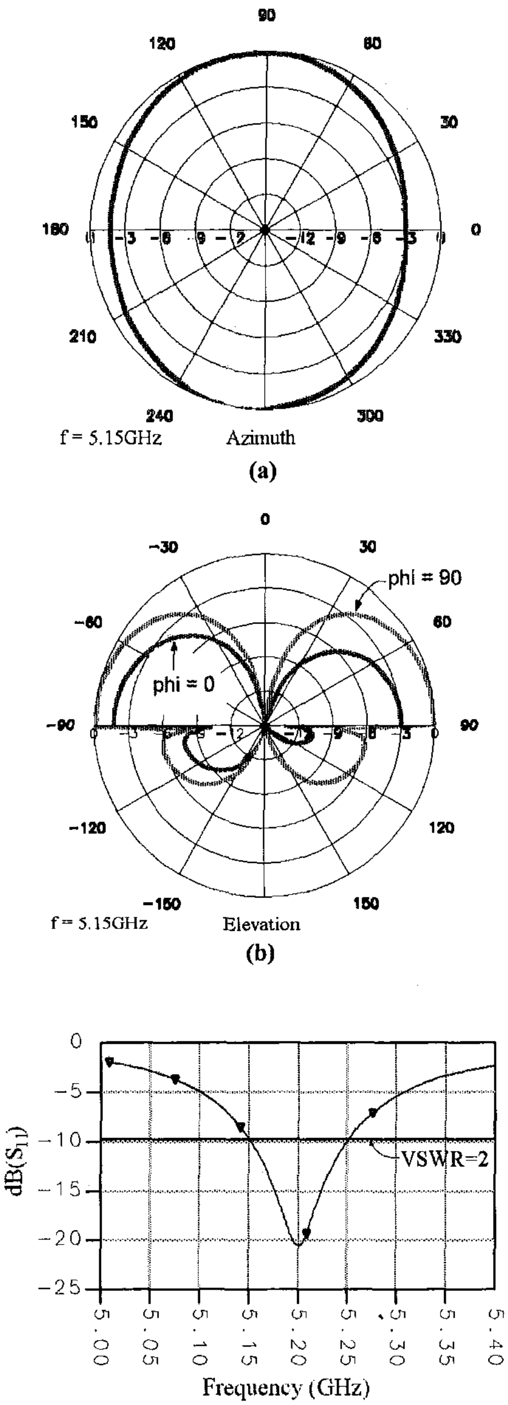

Fig 2: Slot element azimuth (a) and elevation (b) radiation patterns, and return loss (c) for the slot of Figure 1.

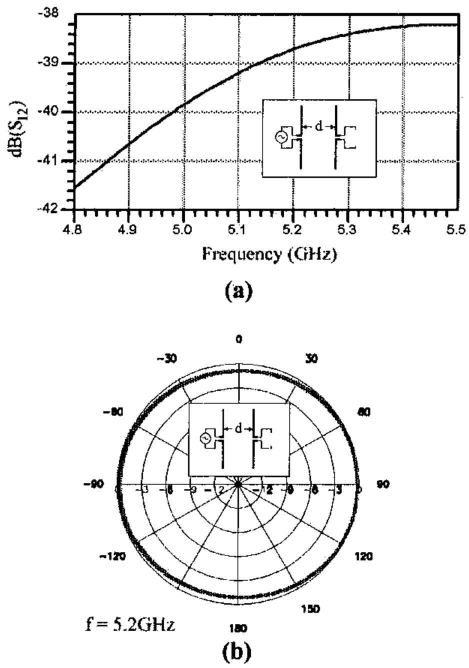

Fig 3: Impedance coupling (a) and azimuth radiation pattern (b) of closely spaced non-resonant dipoles (d=20mm)

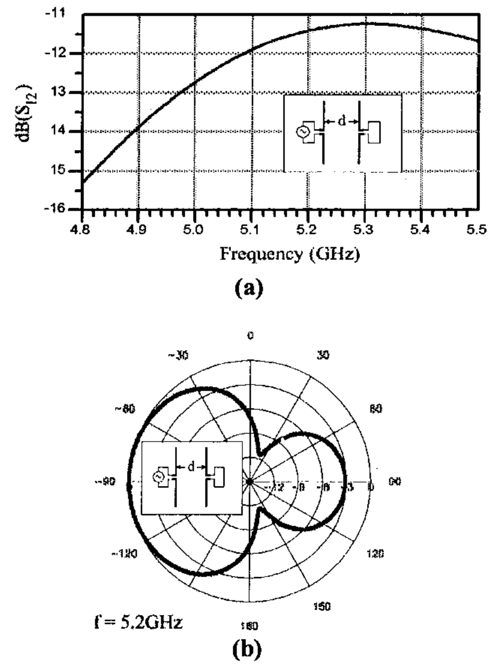

Fig 4: Impedance coupling (a) and azimuth radiation pattern (b) of closely spaced resonant dipoles (d=20mm)

the current distribution in the isolated element. If the change in current distribution is significant, the input impedance of the array will be altered and so the radiation pattern of the array will also be altered. Therefore, if we place a resonant element in close proximity of an active element, the mutual coupling will be significant and the array characteristics will be altered. On the other hand, if we place a non-resonant element in close proximity of the active element, the current induced to the non-resonant element will be minimal and therefore the array characteristics will not be significantly altered [5].

When we are referring to dipole or monopole arrays, driving an element from resonance to non-resonance (or vice-versa) is quite a straightforward process. A dipole with its input short-circuited is a resonant element, while when its input is open-circuited the dipole is driven out of resonance. Figure 3 shows the mutual coupling characteristics (Figure 3a) and azimuth radiation pattern (Figure 3b) between two dipoles with an inter-element spacing of 20mm, working at 5.2GHz. The first dipole is directly driven by the RF signal, while the second is open-circuited. In Figure 4 we can see how these characteristics of the two element dipole array change, when the second dipole is driven into resonance (short-circuited). In this case, the parasitic resonant dipole acts as a reflector due to the currents coupled on its surface and most of the radiated energy is directed at angles near phi = -90°.

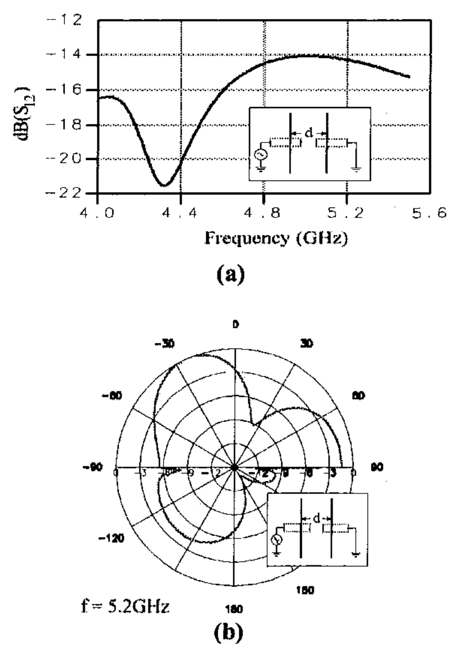

Fig 5: Transmission coefficient parameter S_{12} (a) and elevation radiation pattern at 5.2GHz (b) between microstrip fed slots (d = 20mm)

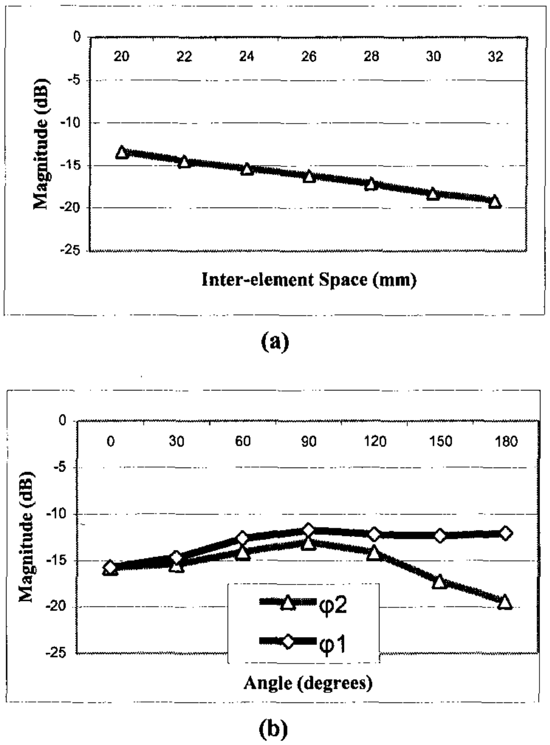

Fig 6: Transmission coefficient S_{12} parameter between two closely spaced proposed slot elements for a number of different interelement spaces (a) and angles (b) (f=5.2GHz)

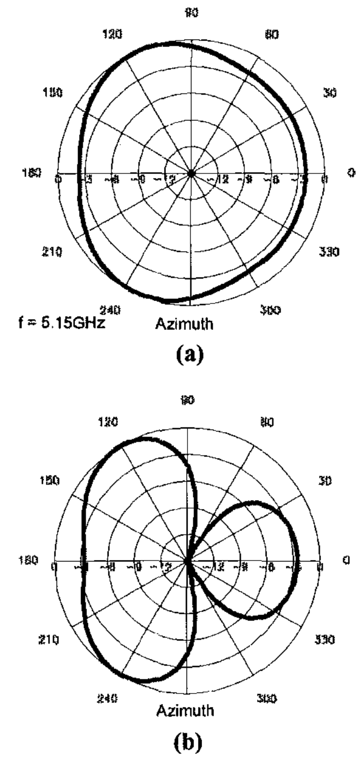

Fig 7: Azimuth radiation patterns of a two-element slot array (d = 20mm), when both elements are fed (a) and when one element is short-circuited (b)

In the case of slot arrays, driving an element out of resonance has proven to be a more complicated matter. Co-planar waveguide (CPW) fed arrays show similar results with the dipole and monopole arrays, but have certain drawbacks that make them non-applicable to our application. They are large in size and produce an omni-directional pattern in the elevation plane. As it is shown in Figure 5, microstrip fed linear slots placed in close proximity produce a radiation pattern that is significantly different of that of a single element, even when the second element is driven out of resonance. The reason is that in microstrip fed slots the feeding of the radiating structure is done through coupling of the element and the microstrip line. The feeding line is not part of the antenna radiating geometry and therefore, we cannot change the antenna resonant characteristics by switching the input impedance of the microstrip.

In contrast to other microstrip fed slot antennas, the proposed element shows improved characteristics. We examine the mutual coupling effects and the radiation pattern of closely spaced proposed elements. Even though the mutual coupling is considerably high (almost equal to the resonant case of two dipoles) for a number of different inter-element spaces and angles (Fig 6), we can see that the coupling does not change significantly with inter-element space and for a number of angles. The radiation pattern of the array is not considerably altered when the second element of the array has input impedance equal to zero (Fig 7a). These results have motivated us to design a switched beam circular array consisting of a central element and a number of peripheral active elements. The central element is driven at all times, while the peripheral elements are driven according to the desirable radiation pattern. The next section presents the switched array made up of the described printed slot antenna elements.

4. THE SEVEN-ELEMENTS ANTENNA ARRAY

The proposed antenna array consists of a central element and six peripheral elements. The radiation layer of the proposed array with an inter-element space of $\lambda_g/2$ at 5.2GHz is shown in Figure 8. The central element is always connected to the RF signal, while the peripheral elements are switched either

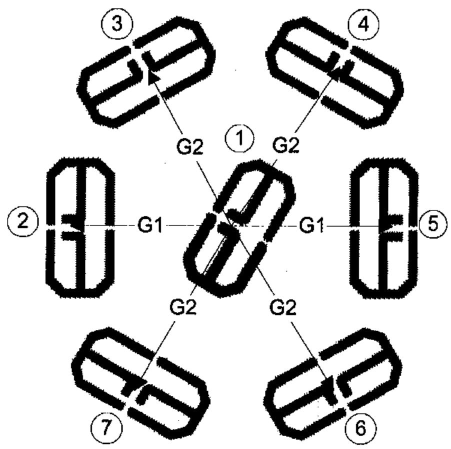

Fig. 8: Antenna array radiation layer. Central element's dimensions as in Figure 1, a=8.5mm, b=18.5mm, d=0.8mm, W1=5.6mm, W2=2.5mm, L1=7.7mm, L2=3mm, S1=1.1mm, S2=1.6. Spacing G1= 20mm, G2=25mm.

to the signal path or to the ground. The signals driven to the peripheral elements in respect to the signal on the central element show a constant phase shift of 270° due to propagation delays and switch phase shifts. An analytical method was used to show that by digitally controlling the state of SPDT switches, multiple overlapping patterns, including an omni-directional pattern, can be produced.

Because of mutual coupling effects encountered between the elements of the array, the position of the peripheral elements and the dimensions of the central element had to be carefully computed in order to resonate at 5.2 GHz. The peripheral elements' spacing from the central element was also modified from the mutual 20mm distance. The distance of elements 2,3,5 and 6 was set to 25mm, while elements' 4 and 7 remained at 20mm. With this configuration we observed a bandwidth of 2% (Fig 9), and an antenna efficiency of above 77%.

The design was placed on an infinite ground plane, over a substrate with a dielectric constant of ε_r=2.2 and a height of h=0.813mm. The effect of the feeding network geometry on the antenna characteristics was not taken into account. The proposed array, as is shown in Figure 8, was simulated and multiple radiation patterns were produced. Table 1 summarizes some of the different feeding patterns that we introduced to the array and Figure 10 shows the corresponding radiation patterns, as well as some additional radiation patterns.

We can see that the directivity of the array does not become greater when we feed more than two peripheral elements. By

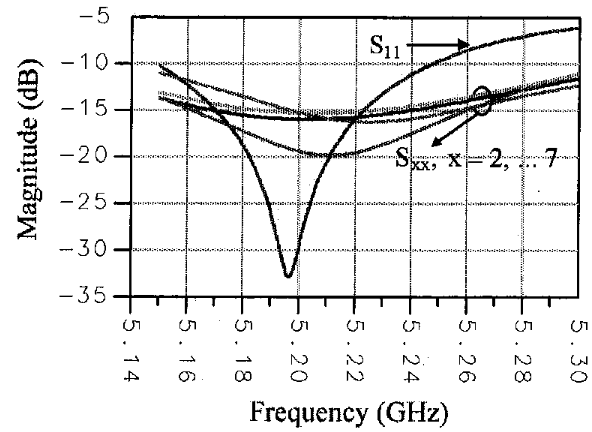

Fig. 9: S parameters of the proposed array

Table 1: Examples of beams at different feeding patterns

Elements Fed	Elevation peak (deg)	Azimuth peak (deg)	Directivity (dBi)
1	90	177	5.5
1,3	90	57	6.23
1,4	90	330	6.37
1,3,4	57	87	7.21
1,4,5	63	21	7.91
1,5,6	81	336	8.56
1,4,5,6	63	0	7.2

activating for example three peripheral elements, we see that we have a lower directivity, but we do produce peaks and nulls in different angles than other configurations. If the number of diverse peaks and nulls of the array is not a crucial issue, we could therefore adjust the feeding network accordingly. We do need a smart feeding technique for the proposed array, in order to have a constant level of power fed into the array, regardless of the number of active elements, without changing the power dissipation of the system. However the complexity and cost of such a feeding network is far less than that of a phased array with the same number of antenna elements. Moreover, the antenna diversity functions remain unaltered and only the total number of diverse beams is increased. Such an approach reduces the processing load of the baseband processor, thus decreasing the total power dissipation.

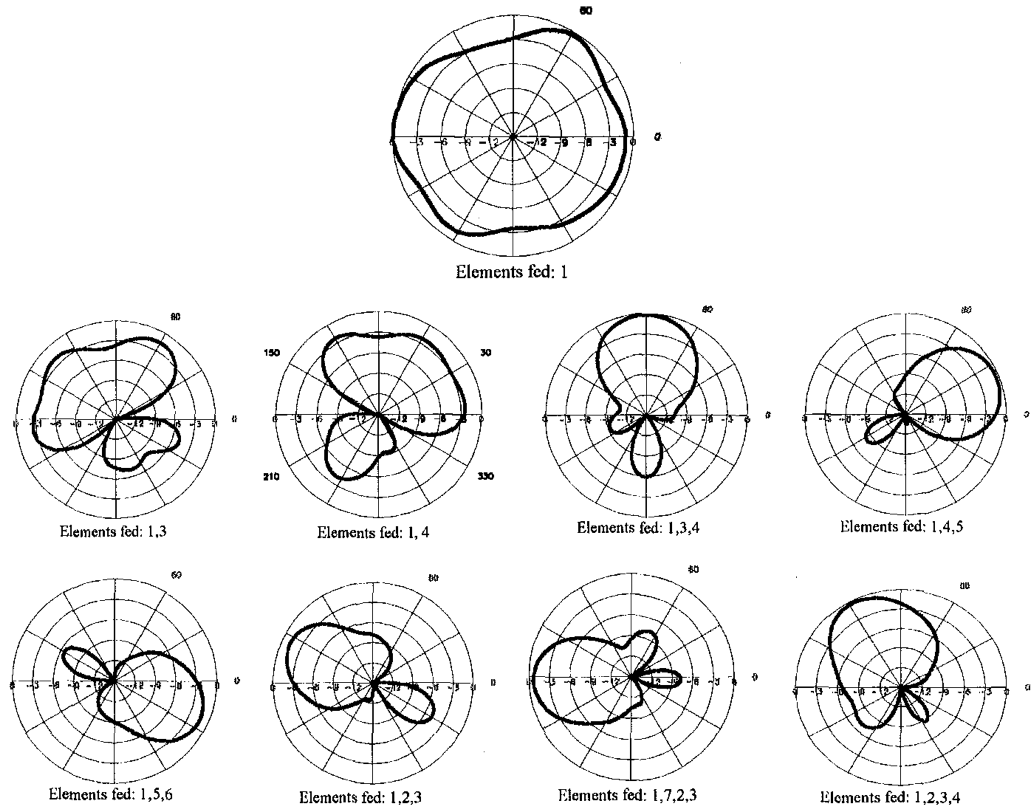

Fig 10: Some of the antenna array azimuth radiation patterns

5. CONCLUSION

The proposed design satisfies the need of an omni-directional indoor communications antenna, while at the same time it can produce multiple overlapping wide and narrow beam patterns. The omni-directionality is needed in order to implement the hidden terminal back-off and assosiation/disassosiation algorithms in next generation wireless systems, while pattern diversity is needed to effectively confront the problems induced by the noisy indoor channel to the highly demanding wireless applications. Moreover the overlapping patterns that can be produced by the proposed array may open new horizons to signal tracking algorithms of next generation wireless systems.

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BIOGRAPHIES

Antonis Kalis was born in Athens, Greece in 1974. He received the Electrical Engineering Diploma degree in 1997 from the Department of Electrical Engineering and Computer Technology at the University of Patras, Patras, Greece. In September 1997, he joined the Laboratory of Electromagnetics at the University of Patras participating in various R&D projects for the Greek Government and the European Union, as a research staff member. Antonis Kalis is a member of the Technical Chamber of Greece.

Theodore Antonakopoulos was born in Patras, Greece in 1962. He received the Electrical Engineering Diploma degree in 1985, and his Ph.D. degree in 1989 from the Department of Electrical Engineering at the University of Patras, Patras, Greece. In September 1985, he joined the Laboratory of Electromagnetics at the University of Patras participating in various R&D projects for the Greek Government and the European Union, initially as a research staff member and subsequently as the senior researcher of the Communications Group. Since 1991 he has been on the faculty of the Electrical Engineering Department at the University of Patras, where he is currently an Assistant Professor. His research interests are in the areas of data communication networks, LANs and wireless networks, with emphasis on performance analysis, efficient hardware implementation and rapid prototyping. He has more than 50 publications in the above areas and is actively participating in several R&D projects of the European Union. Dr Antonakopoulos is a Senior member of IEEE, serves in the Program Committee of the IEEE International Workshop on Rapid System Prototyping, and is a member of the Technical Chamber of Greece.

Vassilios Makios was born in Kavala, Greece. He received his electrical engineering degree (Dipl. Ing.) from the Technical University in Munich, Germany in 1962 and the Ph.D (Dr. Ing.) from the Max Planck Institute for Plasmaphysics and the Technical University in Munich in 1966. From 1962-67 he was Research Associate in the Max Planck Institute for Plasmaphisics in Munich, where he was associated with microwave interaction studies on plasmas. He served as assistant professor 1967-70, associate professor 1970-73 and full professor 1973-77 in the Department of Electronics, Carleton University in Ottawa, Canada, where he was involved with teaching and research in microwave and optical communications, radar technology, remote sensing and CO_2 laser development. From 1977 he is an honorary research professor of Carleton University. From 1976 he is professor of engineering and director of the Electromagnetics Laboratory in the electrical engineering Department of the University of Patras in Greece, where he is involved in teaching and research in microwave and optical communications, data communications networks, LAN's MAN's, B-ISDN and ATM technology with emphasis on efficient hardware implementations and rapid prototyping. His laboratory is actively participating in EU ACTS & ESPRIT R&D projects e.g. LION, DISTIMA, PANORAMA, COBUCO etc. In 1986-87 he spent his sabbatical year at the R&D laboratories of SIEMENS in Munich. He is also involved in research in photovoltaic systems. He has published over 130 papers and numerous patents in the above fields. He has participated in the organizing committees of numerous IEEE and European Conferences and was the Technical Program Chairman of the 5th Photovoltaic European Community Conference in Athens 1983 and Co Chairman of the EURINFO 1988 Conference of the European Community. He is the recipient of the silver medal (1984) and the golden medal (1999) of the German Electrical Engineering Society (VDE). He is a senior member of the IEEE, member of the Canadian Association of Physicists, the German Physical Society and the VDE, Professional Engineer of the Province of Ontario and the Greek Technical Chamber. He is currently Dean of Engineering from 1997 todate and served also as Dean of engineering in the period of 1980-1982. For the past twelve years he serves as the Vice president of the research committee of the University.